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Small Business Innovative Research (SBIR) Technical Report

Integrating a Motion Base into a CAVE Automatic Virtual Environment: Phase I

by

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14. ABSTRACT
Report developed under SBIR contract for topic A00-170. Four research issues to determine the technical feasibility of adding motion to a CAVE Automatic Vehicle Environment (CAVE) were investigated: what is the most effective motion base configuration, which vehicle cues are best presented through the motion base, which vehicle cues are best presented through the visual display, and how should the visual scene be compensated based on the movements of the motion base and the driver. A CAVE-based motion simulator was developed. Researchers drove the simulator to evaluate its performance with several different motion, head tracking, and visual compensation schemes. The primary results were: drivers perceived little difference between head tracking methods; roll, pitch, and vertical cueing were best presented through the motion base; visual scene compensation requires more research; the simulator as developed requires higher visual update rates to be effective; and finally simulator sickness may be an issue and needs to be investigated further. Successful system development may support TACOM's vehicle design process.

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Summary

Realtime Technologies, Inc. (RTI) researched the technical feasibility of adding realistic motion to an immersive virtual reality device known as the CAVE Automatic Virtual Environment (CAVE) system.

Phase I of this Small Business Innovative Research (SBIR) project identified four key research issues that must be investigated to successfully implement a motion base in a CAVE system:

- What is the most effective motion base configuration?
- Which vehicle motion cues are best presented through the motion base?
- Which vehicle motion cues are best presented through the visual display?
- How should the visual display scene be compensated based on the movements of the motion base and the driver?

Since no CAVE systems integrated with motion bases have been developed in the past, RTI developed a "first-cut" CAVE-based motion simulator during Phase I. TACOM and RTI personnel drove the simulator to evaluate its performance with several different motion, head tracking, and visual compensation schemes.

The primary Phase I assessment results were:

- Drivers perceived little difference between head tracking methods
- Roll, pitch, and vertical cueing were the best motion cues to present through the motion base
- Visual scene compensation requires more research
- The simulator as developed requires higher visual update rates to be effective
- Simulator sickness may be an issue and needs to be investigated further

The evaluation results will be used to direct the Phase II research and development plan.

Introduction

Background and Scope

RTI researched the technical feasibility of adding realistic motion to a CAVE system.

Phase I of this SBIR project identified four key research issues that must be investigated to implement a motion base in a CAVE system:

- What is the most effective motion base configuration?
- Which vehicle motion cues are best presented through the motion base?
- Which vehicle motion cues are best presented through the visual display?
- How should the visual display scene be compensated based on the movements of the motion base and the driver?

Other important design factors to consider are the speed at which the visual display scene can be compensated and methods to maximize the visual update rate.

These issues presented several major challenges. First, no CAVE systems integrated with a motion base have been developed, so a literature review cannot help answer these questions directly. Furthermore, research on non-CAVE motion base simulators cannot be directly applied because of fundamental design differences. For example, unlike the CAVE system, typical motion base simulators have the visual display mounted on the motion base and do not use head tracking to perform scene compensation.

Moreover, each research question is affected by at least three factors: human perception of the cues presented by the motion-enhanced CAVE system, technical performance of each stand-alone subsystem, and technical performance of the integrated simulator.

Since both human perception of the motion cues and technical performance of the integrated simulator are essential to solving any of the key research issues, an actual CAVE simulator with motion base must be tested. Yet this presents a "catch 22" situation, since this type of simulator does not exist yet. Consequently, RTI used an iterative approach: the spiral research and development cycle.

The spiral development cycle in this case consists of the following three stages: design, implementation, and assessment. The research spiral repeats over each stage until the final product has been designed. RTI initiated the first iteration of the spiral development cycle during Phase I. Concurrently, RTI performed a literature search on motion washout algorithms, motion cueing methodology, visual scene compensation, and head tracking.

Literature Review

Motion Requirements

In order for a CAVE system to simulate driver performance accurately, it must provide a safe operating environment and elicit operator responses similar to actual driving behavior. To accomplish this, a CAVE system must perform well in the following motion-related areas: visual gaze stability, simulator sickness, realism (or face validity), and performance validity.

Visual Gaze Stability

Visual gaze stability, the ability to maintain eye fixation on a particular target, depends upon human reflexes such as the vestibulo-ocular reflex (VOR) and the optokinetic nystagmus (OKN). VOR is a reflex that counter-rotates the eye relative to the head in order to compensate for head motion during locomotion, thereby stabilizing the direction of the gaze in space. OKN is an oscillation of the eye consisting of a slow movement and a fast movement that allows the tracking of objects as they rotate past in the visual field. When a human moves or tracks objects, dynamic visual acuity, the measure of visual performance while moving, depends upon the ability of the VOR and OKN systems to maintain fixation. Both the VOR and OKN rely on sensory inputs from the vestibular system.

Motion cues are required to provide proper gaze stability and in turn dynamic visual acuity (Selkurt, 1984). Poor motion cues could reduce the effectiveness of visual gaze stability.

In a CAVE environment, where the motions of the head are tracked, position tracking errors can also lead to reduced visual gaze stability. This reduced visual gaze stability will result in lower visual acuity and may lead to simulator sickness (Kalawsky, 1993).

Simulator Sickness

Driver performance may degrade if simulator sickness occurs. Subjects may change their behavior (e.g., limit head movements, change eye scanning patterns), in an attempt to minimize sickness (Kennedy, 1987). Any study with a large incidence of simulator sickness may not reliably predict real-world results.

Puig (1971) presented the concept of cue conflict as a possible cause of simulator sickness. In fixed-base simulators, he hypothesized that there would be cue conflict between the apparent motion seen on the visual display and the lack of any corresponding real motion of the simulator. He therefore recommended the inclusion of motion to reduce simulator sickness.

In fact, studies of driving simulators with motion have indeed shown a substantial reduction in simulator sickness. Casali and Wierwille (1980) found a decrease in simulator sickness when a simulator had both lateral and rotational motion as opposed to only rotational motion. Romano and Papelis (1994) found that 33% of subjects in a driving simulator study reported sickness symptoms without motion cues while only 10%

of subjects reported sickness symptoms when performing the same scenario with motion cues.

Because of these findings, it is recommended that simulators with large fields of view such as a CAVE system utilize a motion base to minimize simulator sickness (Cohen, 1995).

Realism and Performance Validity

Realism, also known as face validity, measures the driver's subjective response to the realism of the simulation. Performance validity correlates the driver's performance in the simulator with that of the driver in the actual vehicle. While realism is often reported in studies, very little research has been performed on performance validity. Motion in simulators has been shown to have an effect both on reported realism and on driver performance.

Bray (1972) reported several findings when comparing an aircraft simulation with and without motion cues. Pilots reported an increase in realism with motion; namely, "They [the pilots] agreed that the task of coping with a simulated outboard engine failure on take-off closely approximated that experienced during actual flight drills." Similarly, Bray also reported reduced operator performance in the simulator without motion cues; specifically, "Comparison maneuvers, conducted with no simulator motion, demonstrated a reduction in the capability of the pilot to stabilize the simulated aircraft."

In the case of TACOM's CAVE environment, therefore, motion cues will likely become an important factor when assessing new vehicle designs.

Motion Control Logic

The actual motion of a vehicle typically extends far beyond the limited motion of the simulator's motion base (several miles as opposed to several feet). Therefore, an algorithm is needed to transform the actual vehicle motion into excursions that provide the required motion cues, yet remain within the capability of the motion base. These algorithms are typically referred to as motion control logic, or washout algorithms.

The motion control logic needs to replicate in the simulator the angular velocities and linear accelerations that are normally detected by the human vestibular system in a real vehicle. If this is performed well, human drivers in simulators will feel as if they are in actual cars. Several different widely-used washout algorithms are described below.

Classical Algorithms

Classical algorithms, the first type to be adopted, use high-pass filters to eliminate a vehicle's low frequency, high-amplitude motions. These also provide tilt coordination in order to recover some of the low-frequency acceleration cues lost due to the high-frequency filtering. An example of the classical filter is given in Figure 1.

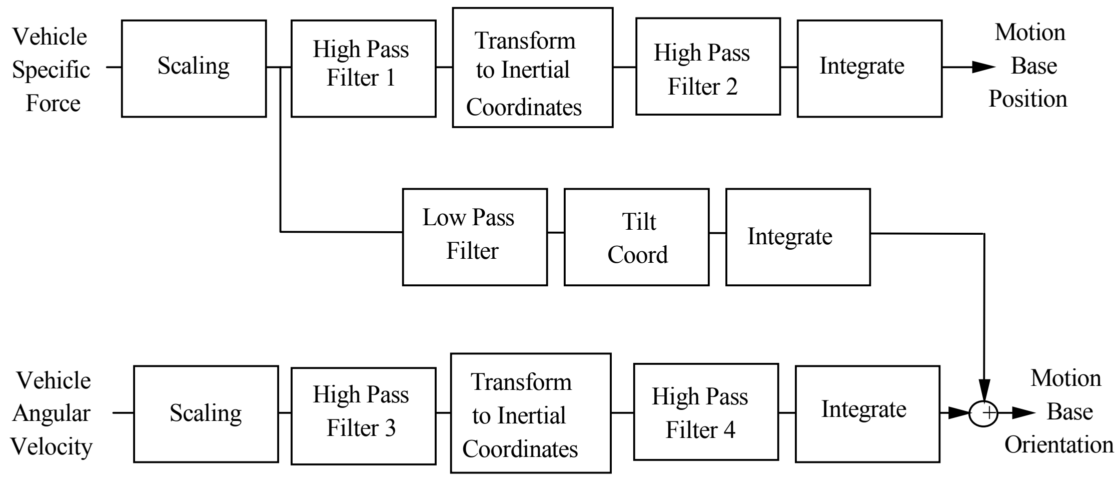

Figure 1: Classical Washout Algorithm

The inputs from the vehicle dynamics are the vehicle's specific forces (defined as $f = a - g$) and the angular velocity in the vehicle's local coordinates. The parameters depend upon the type of vehicle, its path, and the geometrical configuration of the motion base (Garrott, 1993). Selecting the parameters for the digital filters is a difficult trade-off between maximizing cue recovery while eliminating the motion commands outside the motion base limits.

The vestibular system can detect specific forces over a wide range of frequencies, down to 0 m/s/s. Angular velocities, on the other hand, are detected only in a pass band (Young et al., 1969). In addition, there is a threshold below which angular velocities are not sensed (Young et al., 1969).

This discovery led to the development of motion control logic that uses changes in tilt to represent changes in specific force. This form of cueing is frequently called "tilt coordination." The simulator is rotated (or tilted) so that the gravity vector in the simulator is aligned in the same direction as the total specific force vector would be in the actual vehicle.

Without any linear acceleration of the simulator cab, the correct direction (though not the correct magnitude) of the specific force can be represented. If the change in tilt angle is introduced slowly enough, the rotation cue cannot be perceived by the simulator participant.

Coordinated Adaptive Algorithm
Another type of logic used widely in flight simulation is the coordinated adaptive algorithm. Although quite similar to the classical algorithm in flow, this algorithm systematically varies scaling factors, high-pass filter parameters, and low-pass filter parameters in real time to minimize a cost function. As the motion base moves closer to its physical limits, the parameters adjust to reduce the amount of additional motion commanded. Then, as the motion base returns to its center, the digital filter parameters adjust to allow more motion.

Head Tracking Systems

The discussion below outlines the various tracking technologies described in the literature. The information in this section comes chiefly from Latham (1998) and May et al. (1999).

Magnetic Trackers
Magnetic head tracking, typically used in CAVE environments, measures a magnetic field’s strength at several discrete locations. To create the field, a transmitter containing three electromagnetic coils, at right angles to each other, is set up in a stationary location. A receiver, also containing three orthogonal coils, moves within the field. Voltages measured on the receiver's coils are compared to the voltages sent out on the transmitter in order to determine position and orientation.

Advantages of these trackers are their small size and their ability to track multiple objects simultaneously through visual obstructions. However, the receivers must be connected by a wire to the tracking system, their range is limited, and the magnetic field is affected by metal objects in the room.

Magnetic tracking systems also produce a lot of noise. Although much of the noise can be eliminated by filtering, such filtering introduces lag in the system.

Optical Trackers
Three types of optical trackers can be found in the literature: camera-based systems, active-target-based systems, and position-sensing devices (PSDs).

Camera-based systems typically mount a camera within the environment. Either reflective dots or infrared-emitting diodes are then attached to the subject. The dots appear as bright spots in the camera field. Image processing software is used to calculate a heading and elevation for each dot. Camera-based systems are slow because of their lengthy computation time. Moreover, it can be difficult to distinguish between multiple targets, and occasionally some targets may be occluded.

Active-target-based systems use an infrared laser beam to track subjects. The beam is spread into a plane, and it optically sweeps up and down in elevation. Sensors attached to the subjects detect the time at which the plane sweeps past. A second beam, swept in heading, calculates the line to the target. Although quite accurate, active-target-based systems usually are very expensive.

A third type of optical tracker is the position-sensing device (PSD). A PSD is a semiconductor that locates a single bright spot in a dark field. The PSD produces two voltages proportional to the heading and elevation of the spot. Using multiple spots and PSDs, position and orientation can be calculated. Due to data rate limitations, PSDs can track only a few targets at a time.

All three types of optical tracking systems require an unobstructed line-of-sight.

Inertial Trackers

Inertial trackers consist of accelerometers and gyroscopes. An accelerometer is a mechanical device that measures linear acceleration. Gyroscopes measure angular rate. The outputs from inertial sensors must be integrated (twice for the accelerometers and once for the gyroscopes) to obtain a position measurement.

Inertial trackers are small and have a high update rate. The operating environment does not adversely affect them. However, offset errors, or "drift," can accumulate during the integration process. Typically, inertial tracking is performed with a secondary absolute tracking system to correct for these offset errors. The inertial system provides high-frequency relative information and reduces the delay of the tracking system, while the absolute tracking system provides low-frequency absolute information.

Kalman filters are typically used to integrate the inertial and position information. However, effective Kalman filtering requires an accurate noise model of the inertial sensor, which is not always available.

Mechanical Trackers

Mechanical trackers consist of a set of mechanical linkages between a fixed position and the tracked position. Several potentiometers, encoders, and/or linear velocity/displacement transducers (LVDT) measure the linkage positions relative to each other. These positions, combined with kinematic information, allow the tracked position to be calculated relative to the fixed position. The entire mechanical tracker can be moved as long as a separate non-mechanical tracker is used to track its "fixed" position.

Mechanical trackers are very accurate and reliable, with very small latency, yet they can be cumbersome to use. Not only can they severely limit the user's motion, they are also difficult to fit. Another limitation of the mechanical tracker is its inability to measure a subject's absolute location.

Acoustic Trackers

Acoustic trackers use ultrasonic sound transferred among three microphones and three emitters. The three microphones are kept fixed, while the three emitters are placed on the tracked subject in a fixed position relative to each other. The sound's flight time from each emitter to each microphone is used to calculate nine distances -- one for each microphone and emitter pair. Using the static layout of the microphones in the room and the emitters on the subject, these distances can be translated into a position and orientation.

Acoustic trackers are inexpensive, small, and work over a long range. However, their results can be distorted by ambient noise in the room. Also, in order to produce accurate results, a constant line of sight must be maintained between the emitters and the microphones.

Predictor Algorithms for Head Trackers

Because head trackers introduce noise and lag, a filter is often used to reduce signal noise and to predict the future head position. The typical predictor algorithm used is a Kalman filter.

Liang et al. (1991) was one of the first groups to apply the Kalman filter in a head tracking environment to compensate for the lag in the orientation data. They also used a Gauss-Markov process to model the head movement in the Kalman filter. The Gauss-Markov model can predict a random variable that changes at random times, with a limited rate of change during these times followed by periods of no change. To reduce the noise in the position data, they used a low-pass filter.

Azuma and Bishop (1994) used a different sort of predictor algorithm with a hybrid optical and inertial head tracking system. The inertial system provided velocity and acceleration information about the head movement. This velocity and acceleration information was used in a closed-form solution to integrate the position information forward in time. They also used a Kalman filter to eliminate noise in both the optical and inertial tracking systems.

Finally, Wu et al. (1994) used a Grey Model to predict future head position. A Grey Model consists of a set of difference equations that are fit to a sequence of measured raw data. The equations can then be used to predict the next value of a sequence given the previous data elements in the sequence.

Methods, Assumptions, and Procedures

Final Simulator Configuration

RTI applied the best available knowledge and created innovative research techniques to develop the first-ever CAVE simulator with a motion base.

Throughout the process, RTI chose design specifications in order to minimize technical and monetary risk. Yet these choices would be moot unless a functioning motion base CAVE simulator could be developed by the end of Phase I.

Therefore, the goal of Phase I was to create a motion base CAVE simulator for minimal cost and time while maximizing system performance. Moreover, the initial design should allow for future investigation into potential motion cues in the CAVE system.

The final Phase I design employed the following elements:

- TACOM's current CAVE environment, including existing head tracking, projectors, image generator, display software, and audio software. Division's dvs software generated images and performed head tracking, and was integrated with RTI's SimCreator using Division's VCLib. Multigen-Paradigm's Audioworks software generated the audio cues. (TACOM's CAVE environment uses an Silicon Graphics Inc. Infinite Reality II system (SGI) for its image generation.)
- RTI's SimCreator software for system integration.
- RTI's General Vehicle Dynamics System (GVDS) for the vehicle dynamics. A model of a High Mobility Multipurpose Wheeled Vehicle (HMMWV) previously developed by RTI was used as the vehicle dynamics model.
- A Mini Motion Base from Tsunami Visual Technologies, Inc. to generate the motion cues.
- A classical washout algorithm previously developed by RTI to control the motion base.
- A relatively simple, high performance off-road visual database from RTI to maximize the update rate of the image generator.

RTI networked a standard PC with TACOM's SGI. A Digital to Analog (D/A) card and software from Tsunami Visual Technologies was installed on the PC to control the motion base.

SimCreator, a commercially available graphically-based distributed modeling package developed by RTI, was used to model the simulator as the three processes shown in Figure 2.

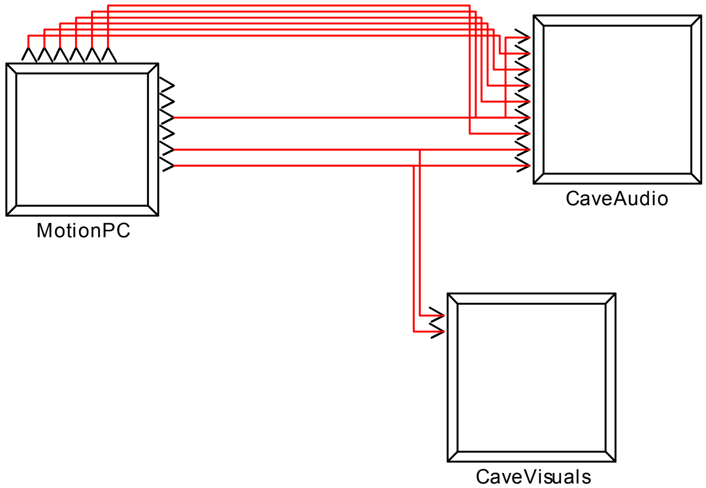

Figure 2: Top-Level SimCreator Model

The processes are MotionPC, CaveAudio, and CaveVisuals. MotionPC runs on the PC and contains the vehicle dynamics, washout algorithm, and motion control software. CaveAudio runs on the SGI and calls the AudioWorks application programmer's interface (API) to implement the audio system. CaveVisuals also runs on the SGI and calls Division's dvs through VCLib to generate the visual scene.

VCLib was called through a standardized interface so that the VCLib scene API can be replaced if necessary in a straightforward way. The standardized interface had the following C function calls:

int gfxInit(void);
- initializes the graphics system

void gfxSetEyePosition(double position[3], double orientation[3]);
- sets the eye position and orientation in the graphical scene

void gfxShutdown(void);
- shuts down the graphics system

int gfxUpdate(void);
- causes the graphics system to draw one frame based on the current head tracker and eye position

int gfxInitTracker(int flag);
- initializes the head tracker and selects internal or external head tracking

void gfxSetTrackerPosition(double position[3]);
- when external head tracking is selected this call overrides the internally calculated head tracking position

Originally, the vehicle dynamics were intended to run on the SGI. During the development cycle, however, it was found that the SGI's processors were at full capacity while performing the visual functions. Therefore, the vehicle dynamics were moved to the PC.

CAVEAudio and CAVEVisuals are very simple groups that directly call their respective software APIs. The MotionPC group is a little more complicated, however, and worth describing in more detail. The MotionPC group, shown in Figure 3, includes software that reads a joystick to allow control of the vehicle.

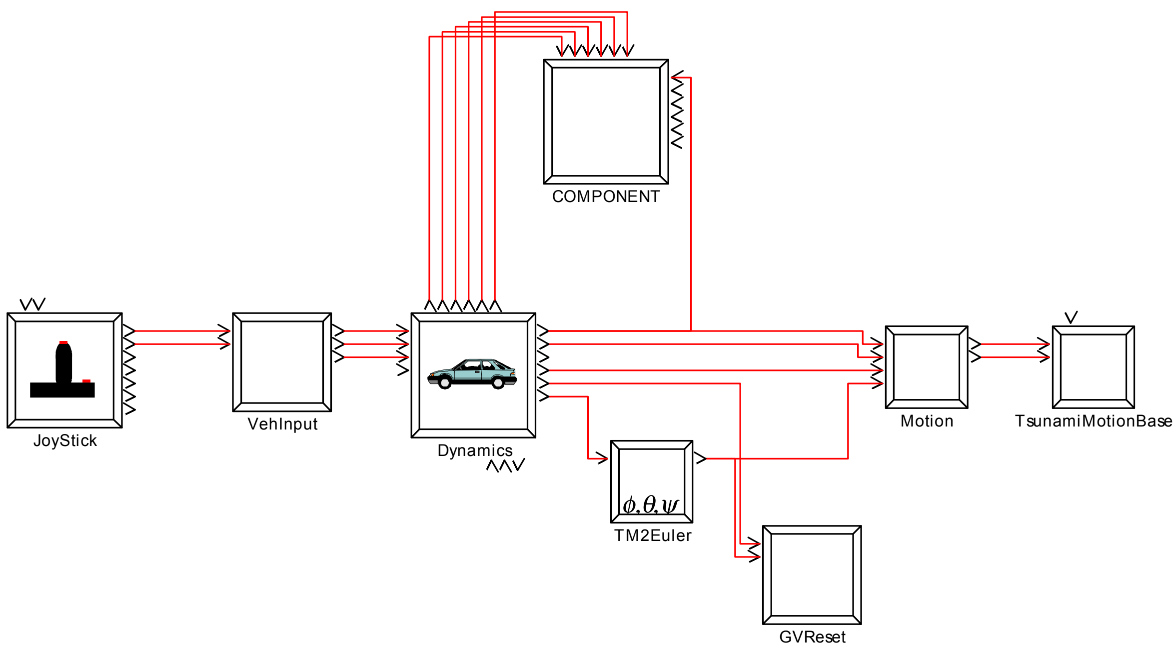

Figure 3: MotionPC Group

The Phase I option includes installing an actual steering wheel, brake pedal, and accelerator pedal on the motion base. The MotionPC group also contains the vehicle dynamics, the washout algorithm, and the Tsunami Motion Base control code.

The dynamics portion of the MotionPC group can be viewed in further detail as shown in Figure 4.

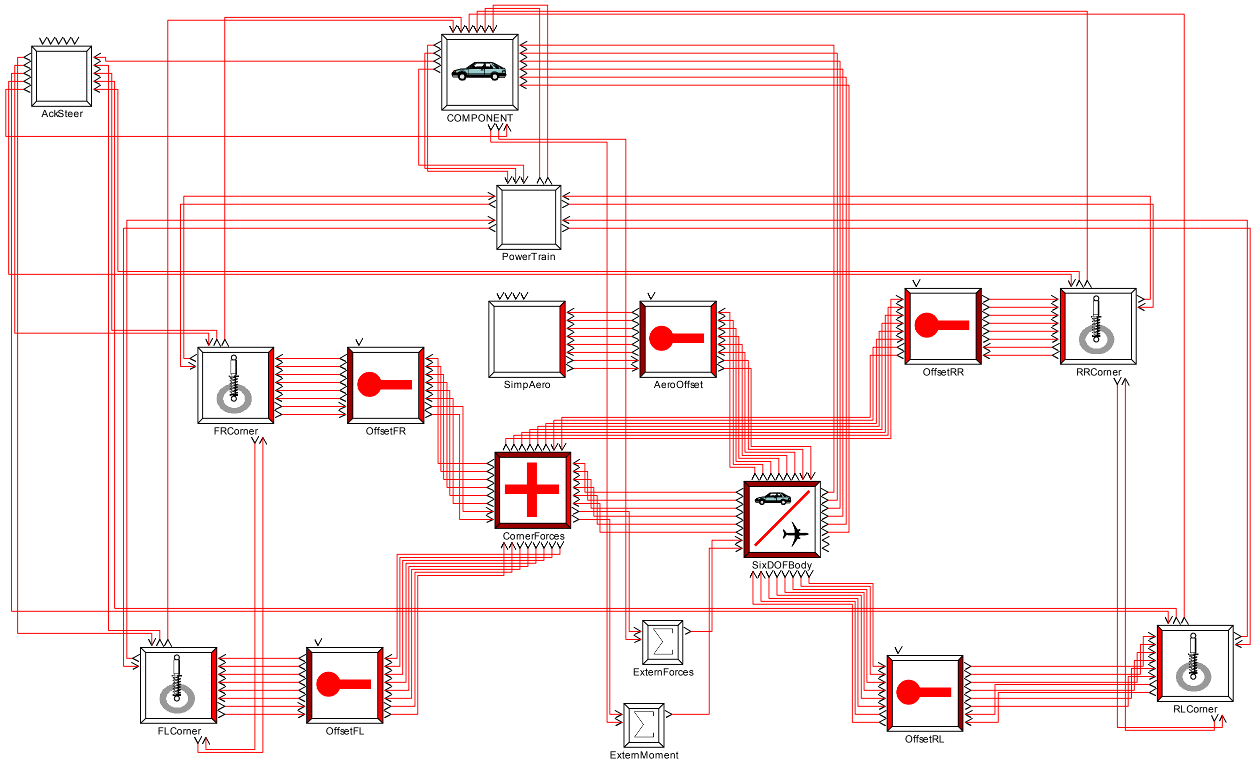

Figure 4: Vehicle Dynamics

The vehicle dynamics model each of the four vehicle corners, the powertrain, and the Newton-Euler equations of motion. Each vehicle corner module takes into account variables such as suspension spring and damping rates, antisquat/antidive geometry, roll height, and auxiliary roll stiffness.

The motion software, shown in Figure 5, consists of six high-pass filters (one each for roll, pitch, yaw, X, Y, and Z) and two low-pass filters for tilt coordination.

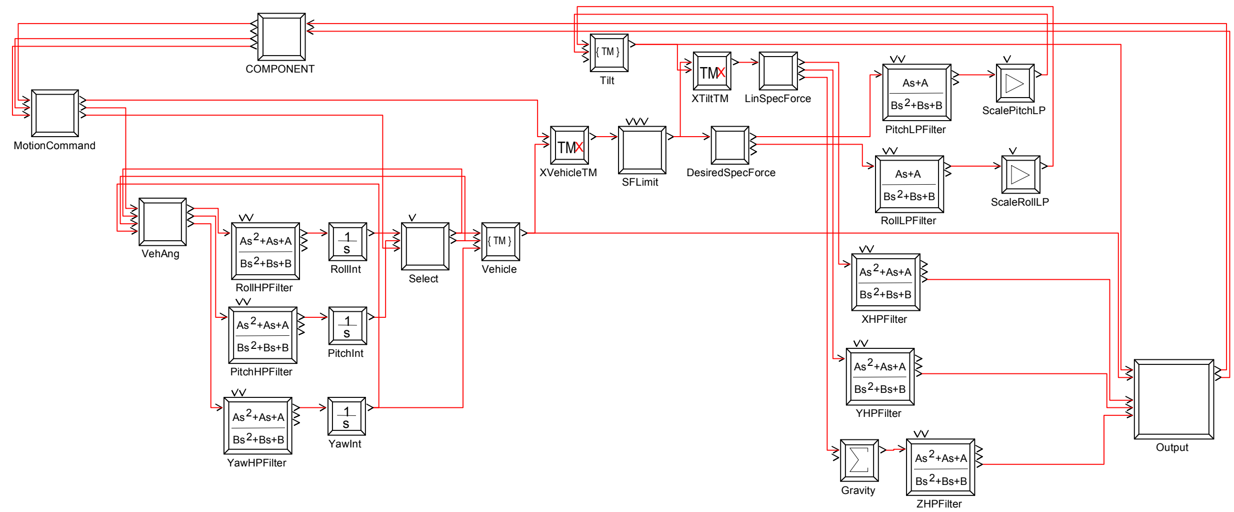

Figure 5: Motion Washout Algorithm

This is a typical configuration for a classical washout algorithm.

The filters are implemented using standard transfer function blocks in SimCreator. Both the vehicle dynamics models and the motion washout algorithm follow closely from the work of Romano (2000).

Figure 6 shows the Mini Motion Base from Tsunami Visual Technologies, Inc.

Figure 6: Motion Base

Besides evaluating driver performance, RTI also worked with TACOM personnel to perform a safety assessment described in Appendix D. The assessment recommended:

"... that signage be placed on or near the simulator describing the maximum payload (occupant) capacity and discouraging potential occupants who may have an existing medical condition (i.e. pregnant woman, persons with back problems or who are prone to motion sickness) from riding the simulator."

This recommendation will be implemented as part of the future research and development effort.

Configurations Studied

As outlined in the Introduction, four questions and two secondary issues must be addressed to implement a motion base in a CAVE system:

- What is the most effective motion base configuration?
- Which vehicle motion cues are best presented through the motion base?
- Which vehicle motion cues are best presented through the visual display?
- How should the visual display scene be compensated based on the movements of the motion base and the driver?

The design also must determine the speed at which the visual display scene can be compensated and methods to optimize that scene. The Phase I assessment stage evaluated several motion, visual, and head tracking schemes to address these issues.

Motion Cueing

The assessment stage evaluated the following four motion control tunings presented by the motion base:

- No motion cues
- Roll and pitch orientation cues only
- Vertical onset acceleration cues and orientation cues
- Onset acceleration cues, orientation cues, and tilt coordination cues

Visual Compensation

In addition to the various motion cues, the assessment included the following two visual compensation approaches:

- Visual system presents the standard scene
- Visual system does not subtract motion base orientation cues

Head Tracking

Finally, the researchers tested three different head-tracking schemes:

- Standard head tracker with standard predictor algorithm
- Current commanded motion base position with standard head tracker orientation
- Predicted valued of the commanded motion base position with standard head tracker orientation

In the second and third head tracking schemes, the head tracker orientation was read using the tracked software, part of VRCo's CAVELib.

In the third case, where prediction is performed, the commanded motion base position has no noise and the derivative of the signal is available. Therefore, algorithms similar to those developed to compensate for graphics computer delays are more appropriate than typical head tracking prediction algorithms. Examples of these algorithms include lead filters (Haug et al., 1990), lead/lag filters (Ricard and Harris, 1978), and predictor algorithms (McFarland, 1988).

McFarland showed that lead filters could introduce substantial magnitude distortion, while Cardullo and George (1993) found that McFarland's predictor provided the best trade-off between performance and accuracy. Therefore, McFarland's was chosen to calculate the predicted motion base position. The McFarland predictor, described in Appendix B, was implemented in SimCreator.

Although a Kalman filter normally performs the head tracking, it could not be used in the third case because the Gauss-Markov equations model only abrupt movement followed by periods of no movement. In this case, the motion base moves continually.

Because the visual scene had a lag of 50 ms (based on statistics taken from SGI's Performer) and the update rate for the motion base was 16 ms (60 Hz), the predictor was configured to predict the motion base position 34 ms into the future. The McFarland algorithms given in Appendix B. Figure 7 shows performance of the algorithm.

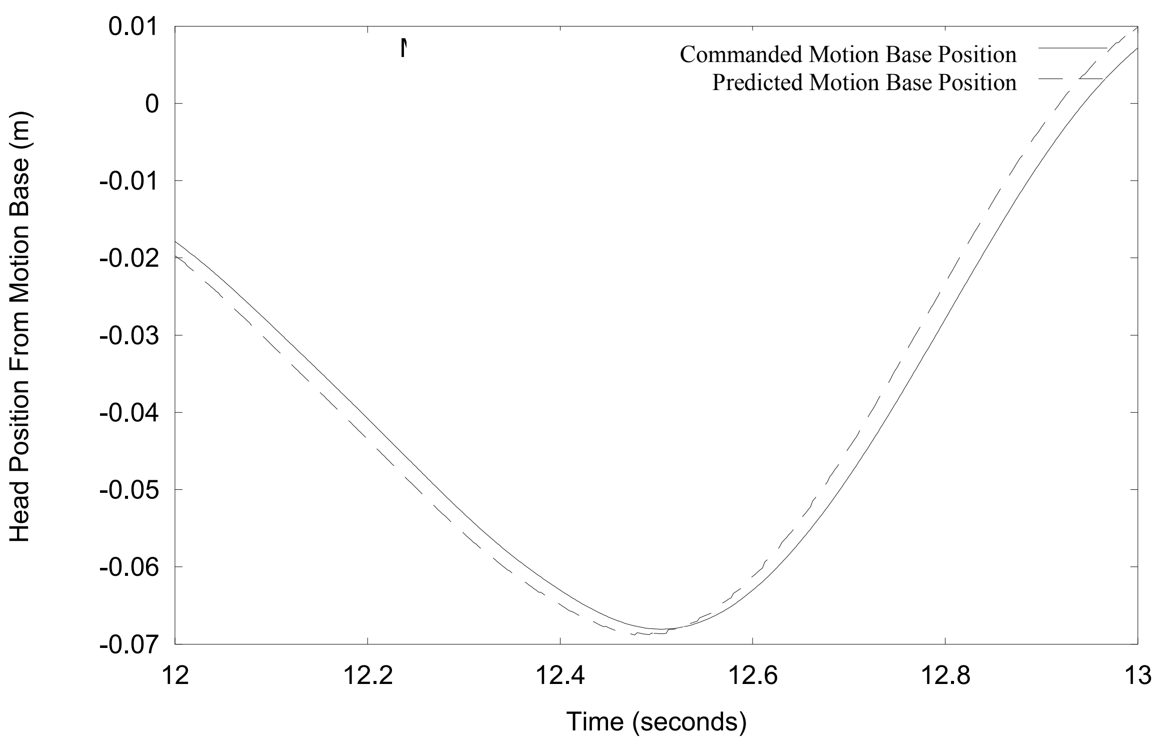

Figure 7: Head Position Prediction

Results and Discussion

Observations

The design stage of the spiral research and development cycle revealed several potential technical challenges. Similarly, the implementation process highlighted additional issues for future study. These observations are summarized below:

- **SimCreator provided reliable distributed real-time simulation.** In addition, the GVDS vehicle dynamics model operated reliably.

- **The dvs system from Division provided unexpectedly low visual update rates.** The SGI for TACOM's CAVE was an Infinite Reality II with three graphics pipelines and eight processors. Each pipeline had two graphics managers. The SGI was configured to render three stereo 1280x512 screens in the CAVE, the equivalent of six standard 1280x512 screens. The off-road database used was intentionally simplified with a low depth complexity. With this configuration, the visual update rate was between 24 and 48 Hz. RTI has seen similarly equipped SGI systems with more complex databases and similar pixel fill (screen layout) requirements run at 60 Hz using SGI Performer.

  Therefore, other rendering software should be investigated to increase the visual update rate.

- **The standard head tracking in the CAVE has significant transport delay.** This delay could lead to substantial driver disorientation. The motion base itself provided much faster information on its position.

- **Integrating new head tracking software into Division's dvs is extremely difficult.** The interfaces are undocumented and there is no example code. In addition Division's VCLib is not a true API. Code developed and linked with VCLib cannot be executed directly but must be launched using dvs.

- **The motion base footprint is very small, limiting the amount of onset cueing that can be generated.** The motion base provided only 1.5 inches of travel in all linear directions. Although this motion base fits well inside TACOM's current CAVE configuration, a larger CAVE would be able to handle a larger motion base and likely would produce better results.

- **Driving with a joystick is highly unnatural**. More typical driver controls, such as a steering wheel, would likely improve the simulation experience.

- **Using the commanded motion to the motion base for head tracking is not the most effective approach.** Because of phase lag in the motion base, the current motion base position should be used for head tracking and a Kalman filter employed to predict the future motion base position.

- **The current motion base design makes it difficult to move the motion base in and out of the CAVE.** Possible improvements including padding and smoothing out the bottom to protect the CAVE floor and attaching retractable wheels to the motion base so that it could be moved in and out of the CAVE quickly and easily.

Configuration Comparisons

Five simulation experts from TACOM, along with RTI's principal investigator, operated and assessed the CAVE simulator with a motion base.

RTI's principal investigator and TACOM's Contracting Officer's Representative evaluated each of the three head tracking configurations. They found no perceptible difference between the three configurations, largely because the amount of head motion generated while driving the simulator was very small -- typically less than five inches, with a maximum motion of 7.2 inches. Because of the lack of perceptible difference, and to minimize the amount of time each person spent in the CAVE, the three head tracking configurations were not presented to the other drivers.

Each driver tested five configurations in the following order:

- Motion base presents no motion cues
- Motion base presents roll and pitch orientation cues only
- Motion base presents vertical onset acceleration and orientation cues
- Motion base presents onset acceleration, orientation, and tilt coordination cues
- Motion base presents onset acceleration, orientation, and tilt coordination cues Visual system does not subtract motion base orientation

The drivers drove each configuration down a simulated gravel road for about two minutes. The gravel road section included left and right turns and steep vertical hills.

After testing each of the second and subsequent motion cue schemes, the drivers were asked to compare each scheme with the prior configuration and identify a preference. Preferences were recorded on an assessment form given in Appendix A and the survey results are summarized in Figure 8:

Option One	Preference		Option Two
No Motion	0	6	Roll and Pitch Only
Roll and Pitch Only	1	5	Roll, Pitch and Heave
Roll, Pitch and Heave	4	2	5 DOF with Tilt Coordination
5 DOF with Tilt Coordination	2	4	5 DOF with Tilt Coordination with motion base orientation cues in visuals

Figure 8: Motion Cue Preferences

The left-center column shows the number of drivers who preferred the first scheme, while the right-center column shows the number of operators who preferred the second scheme.

Some important results from the comparison are:

- **Drivers perceived no differences between the three head tracking methods**
- **All operators preferred some motion cues over no motion**
- **Most drivers preferred roll, pitch, and heave motion cues**
- **Most operators preferred the visual scene to include the motion base orientation when tilt coordination is added**

This last result presents a design dilemma. Although deleting the motion base orientation from the visual scene generates a correct scene perspective, the drivers preferred when the motion base orientation was included. This contradiction should be addressed in future research.

Additional Observations

In addition to configuration preferences, general driver comments were also collected and are summarized below:

- **Graphics seemed to pause intermittently.** When the graphic pausing was investigated after completing the configuration testing, RTI found that the NetWare software slowed down the PC running the motion base and vehicle dynamics. Once the NetWare software was removed from the PC, the pausing was eliminated.
- **Auditory feedback improved the drivers' vehicle control.**
- **Drivers could not clearly see contours of the road (the visual scene was blurry).** The 1280x512 screen resolution, selected to maintain a high visual update rate, stretched the road image significantly. This stretching distorted and obscured the polygons that comprised the image. Because the road contours were difficult to see, drivers reported that the simulator motion did not always feel realistic. Often, a particular road disturbance would be felt but not seen. A more typical 1024x768 resolution could not be used, however, because the projectors were not calibrated for this resolution.
- **Motion cues were most important when drivers traversed the portions of the road with rapid elevation changes.**
- **The CAVE area was uncomfortably hot.** The air conditioning in the CAVE was not sufficient to keep the room cool.

- **The motion base was too close to the front screen.** Although the design intended to place the driver in the center of the CAVE, the seat was actually four inches forward of center. Since the CAVE is an eight-foot cube, this deviation represents an error of about 8%.

- **The large metallic motion base in the CAVE area did not appear to affect the performance of the head tracker.**

- **One driver reported simulator sickness.** One operator reported some feelings of simulator sickness. In addition, two other riders who were not part of the evaluation reported some feelings of simulator sickness.

Simulator sickness has many possible causes and mitigation methods. Kolasinski et al. (1995) presents an excellent summary of the various simulator design s that can increase the chances of simulator sickness. These design attributes that exist in the current CAVE motion base simulator are:

- Binocular viewing
- A single distance between the eyes used for all subjects
- Poor calibration of the visual display system
- Wide visual field of view
- Low graphical update rate
- Low graphical resolution
- Large transport delay (caused by low graphical update rates)
- Motion
- Lack of ventilation

There is an ongoing debate as to whether motion increases or decreases simulator sickness. Several studies presented in the previous Literature Review section suggest that adding motion actually can reduce simulator sickness.

Recommendations

As part of the SBIR Phase II proposal, RTI developed a research plan which included significant work on head tracking. This plan was developed, however, before the Phase I assessment had been done. Once the assessment stage was completed, RTI and TACOM determined that head-tracking methods had little effect on the perceived system performance. Moreover, the assessment revealed that simulator sickness might be an issue worth investigating. Based on the results of the Phase I assessment, therefore, the proposed Phase II work has been modified.

Proposed Research and Development Plan

During the Phase I option, RTI will install a lightweight cab with a steering system, accelerator, and brake. The steering system will have a torque motor to provide feedback.

In Phase II, RTI will perform two more spiral research and development cycles. As in Phase I, each cycle will include a design stage, implementation stage, and assessment stage. However, as more effort will be spent in these design and implementation stages, each spiral cycle in Phase II will take longer.

At the end of the second development cycle in Phase II, a simulation assessment will be performed on a specific wheeled vehicle. RTI will work with TACOM to select the vehicle to be assessed, collect available vehicle data, and model it inside of SimCreator.

Specific objectives of the Phase II effort are:

- **Survey current CAVE users to determine their requirements for a CAVE simulator with a motion base.** Where possible, specific system requirements will be integrated into the CAVE motion system for further assessment.

- **Increase the frame rate of the CAVE simulator and identify and integrate a high-performance immersive visual API to replace Division's dvs system.** This may be Multigen-Paradigm's Vega software or another third party software.

- **Develop a standard software interface that plugs into the immersive visual API as determined above.**

- **Upgrade the motion base to include easily retractable wheels and a smooth padded bottom.**

- **Determine the optimum motion cues, visual compensation, and washout tuning for use with the motion base.** The Phase I research indicates that roll, pitch, and heave are the best motion cues. This result may be due to poor tuning of the tilt coordination system or incorrect visual compensation. Additional research should be performed with a larger driver sample to determine the optimum motion control configuration. This investigation will include an iterative improvement on motion cues presented through either the motion base or the visual system, as well as further tuning of the washout filter's scaling, limiting, and filter parameters.

- **Determine the preferred location of the motion base in the CAVE.**

- **Investigate lower cost immersive systems.** Lower cost systems would allow wider use of the motion base system. Single wall CAVE systems as well as head mounted displays will be investigated. In addition, the performance of these low cost systems will be compared with the CAVE and with simulators with higher performance motion bases.

- **Investigate simulator sickness issues in the CAVE motion base environment.** Several design items identified in Phase I as possible causes of simulator sickness will be improved during Phase II, such as low graphical resolution and update rates, large transport delays, and inadequate ventilation, among others. With the improvements, a tradeoff analysis will be performed to investigate the effect of wide field of view and motion on simulator sickness.

- **Work with TACOM personnel to select a wheeled vehicle for the final assessment and implement the model in SimCreator.**

- **Perform a final assessment of the CAVE configuration with motion base and evaluate the system's ability to assist in the vehicle design and acquisition process.**

Possible Commercial Products

Several commercial products may result from the research into adding a motion base to the CAVE system, including:

- An electric motion base with control software and head tracking configured for use in CAVE environments. This can be a commercial option that can be installed in existing CAVE systems or in new CAVE configurations sold by commercial virtual reality vendors.

- A vehicle cab and control loading system for use on the motion base.

- A complete CAVE-based simulator with motion base that includes both vehicle dynamics and visual databases.

References

Azuman, R. and Bishop, G.; "Improved Static and Dynamic Registration in an Optical See-Through HMD;" pp. 197-204; SIGGRAPH '94 Conference Proceedings; 1994.

Barnes, A.G.; "Operating Experience of a Small Six Axis Motion System Inside a Dome With a Wide Angle Visual System;" AIAA Technical Paper No. 87-2437.

Bray, R.S.; "Initial Operating Experience with an Aircraft Simulator Having Extensive Lateral Motion;" NASA TM X-62, 155; National Aeronautics and Space Administration; Washington, D.C.; 1972.

Brookner, E.; *Tracking and Kalman Filtering Made Easy*; A Wiley-Interscience Publication; 1998.

Brooks, R.R., and Iyengar, S.S.; Multi-Sensor Fusion: Fundamentals and Applications With Software; Prentice Hall PTR; 1998.

Brown, Robert G., et al.; Introduction to Random Signals and Applied Kalman Filtering: With Matlab Exercises and Solutions, 3rd Edition; John Wiley and Sons,;1996.

Cardullo, F.M., and George, G.; "Transport Delay Compensation – An Inexpensive Alternative to Increasing Image Generator Update Rate;" Technical Paper A93-52651 23-09; pp. 95-102; *Flight Simulation Technologies Conference*; AIAA; Monterey, CA; 1993.

Casali, J. G., and Wierwille, W.W.; "The Effects of Various Design Alternatives on Moving-Base Driving Simulator Discomfort;" pp 741-756, *Human Factors*, 22(6); 1980.

Cohen, A., Boehm-Davis, D.A., Burns, M., Hendrickson, C., McCauley, M.E., McGee, H.W., Metz, L.D., Parr, B., Seidle, N., Shepp, L.A., Smiley, A., Taylor, H.L., and Voorhees, J.W.; *Estimating Demand for the National Advanced Driving Simulator*; Transportation Research Board; National Academy Press; Washington, D.C.; 1995.

Garrott, W.R.; "Sizing the Motion Base of the National Advanced Driving Simulator;" Report No. DOT HS 807 979; National Highway Traffic Safety Administration; March 1993.

Haug, E.J., Anderson, D., Berbaum, K., Evans, D., Hinrichs, J., Kim, S-S., Kuhl, J., Lee, W-S., Lenel, J., Stoner, J., Tsai, F-F., Bernard, J., Malwitz, D., Turpin, D., Sinacori, J., Allen, W., and McAreavy, J.; "Feasibility Study and Conceptual Design of a National Advanced Driving Simulator;" DOT HS 807 597; March 1990.

Kalawsky, R.S.; *The Science of Virtual Reality*; Addison-Wesley Publishing Company; New York, NY; 1993.

Kennedy, R.S., Berbaum, K.S., Lilienthal, M.G., Dunlap, W.P., Mulligan, B.E., and Funaro, J.F.; “Guidelines for Alleviation of Simulator Sickness Symptomatology;” NAVTRASYSCEN TR-87-007; Naval Training Systems Center; Orlando, FL; March 1987.
Kolasinski, E.M., Goldberg, S.L., Hiller, J.H., "Simulator Sickness in Virtual Environments", Technical Report 1027, U.S. Army Research Institute for the Behavioral and Social Sciences, Alexandria, VA, 1995.

Latham, R.W.; “Hybrid Optical/Inertial Trackers;” Proceedings of the 1998 IMAGE Conference; The IMAGE Society; Tucson, AZ; 1998.

Lee, W-S.; “Transport Delay Compensation in an Advanced Driving Simulator Using a Nonlinear Driver-Driving Simulator Model;” Technical Report R-87; Center for Simulation and Design Optimization; The University of Iowa; 1990.

Liang, J., Shaw, C., and Green, M.; "On Temporal-Spatial Realism in the Virtual Reality Environment;" pp. 19-25; Proceedings 4th Annual Symposium on User Interface Software and Technology; Hilton Head, SC; 1991.

May, R., Turner, S. Audleman, K. Kassabalides, I.; "Wide Area Tracking for Computer Supported Collaborative Work;" Report for Industrial Engineering 543; University of Washington; 1999.

McFarland, R.E.; “CGI Delay Compensation;” NASA TM-86703; National Aeronautics and Space Administration, Ames Research Center; Moffett Field, CA; 1986.

McFarland, R.E.; “Transport Delay Compensation for Computer-Generated Imagery Systems;” NASA TM-100084; National Aeronautics and Space Administration Ames Research Center; Moffett Field, CA; 1988.

Puig, J.A.; “The Sensory Interaction of Visual and Motion Cues;” pp 55-65; *Naval Training Devices Center 25th Anniversary Commemorative Technical Journal*; Naval Training Equipment Center, Orlando, Florida; 1971.

Ricard, G.L. and Harris, W.T.; “Time Delays in Flight Simulators – Behavioral and Engineering Analyses;” Paper No. 78-1596, AIAA Technical Paper Series; 1978.

Romano, R.A.; “A New Approach to Motion Control Logic for Ground Vehicle Simulators;” Proceedings of the IMAGE VII Conference, The IMAGE Society; Tucson, AZ; 1996.

Romano, R., and Papelis, G.W.; “Assessment of the Capabilities of the Iowa Driving Simulator;” Contract No. DTFH61-92-C-00005; Federal Highway Administration; March 1994.

Romano, R.A.; “Realtime Driving Simulation Using A Modular Modeling Methodology;” SAE Technical Paper Series No. 2000-01-1297; March 2000.

Selkurt, E.E.; *Physiology*; Little, Brown and Company; Boston, MA; 1984.

Toyama, K. Horvitz, E.; "Bayesian Modality Fusion: Probabilistic Integration of Multiple Vision Algorithms for Head Tracking;" Microsoft Research Publication; http://research.microsoft.com/toyama.

Wu, Jiann-Rong and Ouhyoung, M.; "Reducing The Latency In Head-Mounted Displays By a Novel Prediction Method Using Gray System Theory;" pp. C503-C512; Computer Graphics Forum (EuroGraphic '94) 13(3); 1994.

Young, L.R., Meiry, J.L., Newman J.S., and Feather, J.E.; “Research in Design and Development of a Functional Model of the Human Nonauditory Labyrinths;” TR-68-102, Aerospace Medical Research Laboratory; March 1969.

Appendix(es)

Appendix A: Informal Ratings Sheet

Assessment of a Motion Base in the CAVE Environment

Name:

Comparison Pairs:

Option One	Preference		Option Two
No Motion			Roll and Pitch Only
Roll and Pitch Only			Roll, Pitch and Heave
Roll, Pitch and Heave			5 DOF with Tilt Coordination
5 DOF with Tilt Coordination Standard Tracking			5 DOF with Tilt Coordination Motion Base Head Tracking
5 DOF with Tilt Coordination Motion Base Head Tracking			5 DOF with Tilt Coordination Motion Base Head Tracking With Prediction
5 DOF with Tilt Coordination Motion Base Head Tracking with Prediction			5 DOF with Tilt Coordination Standard Tracking
5 DOF with Tilt Coordination			5 DOF with Tilt Coordination with motion base orientation cues in visuals

Comments:

Appendix B: McFarland Predictor

McFarland (1986) gives a good description of his predictor method. Given a signal u with a known derivative v. McFarland's algorithm predicts the signal u at a time T_C seconds into the future using the relationship:

$$u_{k+1} = u_k + (f_0 v_{k+1} + f_1 v_k + f_2 v_{k-1}) T_C \qquad \text{(B.1)}$$

where

$$\begin{aligned} u_k &\equiv u(kT_c) \\ v_k &\equiv v(kT_c) \qquad \text{(B.2)} \\ k &= (0,1,2,...) \end{aligned}$$

To determine the values of f_i in Equation B.1, it is assumed that $u(t)$ can be represented by a sinusoid, specifically $u(t) = e^{jWt}$. If one assumes that $u(t)$ must satisfy Equation B.1 for $W = 0$ and $W = W_0$, where W_0 is a tuning parameter, then defining $U \equiv W_0 T_C$, McFarland shows that:

$$\begin{aligned} f_0 &= \frac{U \sin U - 2\cos U(1-\cos U)}{2U \sin U(1-\cos U)} \\ f_1 &= \frac{2\sin U(\sin U - U\cos U)}{2U \sin U(1-\cos U)} \qquad \text{(B.3)} \\ f_2 &= \frac{U \sin U - 2(1-\cos U)}{2U \sin U(1-\cos U)} \end{aligned}$$

To calculate v_{k+1}, the signal's derivative v must also be predicted T_C seconds into future. This is done by fitting a sinusoidal curve to the signal's derivative of the form:

$$v(t) = g_0 + g_1 \sin(W_0 t) + g_2 \cos(W_0 t) \qquad \text{(B.4)}$$

Assuming that the computer calculating u and v is running at an update interval of Δt seconds and that $\Delta t \neq T_C$ and defining:

$$\begin{aligned} P &= W_0 \Delta t \\ v_n &= v(n\Delta t) \qquad \text{(B.5)} \\ u_n &= u(n\Delta t) \\ n &= (0,1,2...) \end{aligned}$$

then McFarland shows:

$$
\begin{aligned}
g_0 &= \frac{v_n - 2v_{n-1}\cos P + v_{n-2}}{2(1-\cos P)} \\
g_1 &= \frac{(1+2\cos P)v_n - 2(1+\cos P)v_{n-1} + v_{n-2}}{2\sin P} \\
g_2 &= \frac{(1-2\cos P)v_n + 2v_{n-1}\cos P - v_{n-2}}{2(1-\cos P)}
\end{aligned}
\qquad \text{(B.6)}
$$

and

$$
\begin{aligned}
v_{k+1} &= g_0 + g_1 \sin U + g_2 \cos U \\
v_k &= g_0 + g_2 \\
v_{k-1} &= g_0 - g_1 \sin U + g_2 \cos U
\end{aligned}
\qquad \text{(B.7)}
$$

Therefore to calculate u_{k+1}, first g_i is calculated using Equation B.6 and f_i is calculated using Equation B.3, then v_{k+1}, v_k, v_{k-1} are calculated using Equation B.7, and finally u_{k+1} is calculate using Equation B.1.

Appendix C: Potential Vendors for Tracking Technology

Ascension Technology Corporation
P.O. Box 527
Burlington, VT 05402
http://www.ascension-tech.com

Polhemus Incorporated
1 Hercules Drive
P.O. Box 560
Colchester, VT 05446
http://www.polhemus.com

Spatial Positioning Systems, Inc.
12007 Sunrise Valley Drive, Suite 200
Reston, VA 22091
http://members.aol.com/spsie/spatial.html

Origin Instruments Corporation
854 Greenview Drive
Grand Prairie, TX 75050
http://www.orin.com

InterSense, Inc.
73 Second Avenue
Burlington, MA 01803
http://www.isense.com

Fifth Dimension Technologies
P.O. Box 5,
Persequor Park, 0020
Pretoria, South Africa
http://www.5dt.com

Virtual Technologies, Inc.
2175 Park Boulevard
Palo Alto, California 94306
http://www.virtex.com

Sarcos
360 Wakara Way
Salt Lake City, UT, 84108
http://www.sarcos.com

Fakespace Labs, Inc.
241 Polaris Ave.

Mountain View, CA, 94043
http://www.fakespacelabs.com

Fakespace Systems
809 Wellington Street North,
Kitchener, Ontario, Canada, N2G 4J6
http://www.fakespacesystems.com

Appendix D: Safety Assessment Report

U.S. Army
Tank-automotive and Armaments Command

CAVE Motion Base Simulator
Safety Assessment Report

June 2001

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1.0 INTRODUCTION

This report documents the analysis of the CAVE Motion Base Simulator (CMBS) purchased for the U.S. Army Tank-automotive and Armaments Command (TACOM) in Warren, Michigan. This report provides system and component descriptions and a specific hazard analysis of the CMBS.

The scope of this analysis is the systematic assessment of the real and potential hazards associated with the CMBS. This report is an attempt to identify hazards and to discuss the elimination or control of the identified hazards.

2.0 OBJECTIVES

The primary goal is to provide documentation that assists the Tank-Automotive Research, Development and Engineering Center (TARDEC) in obtaining a man-rating status for the CAVE Motion Base Simulator.

3.0 CONCLUSIONS

The CMBS is a commercial motion base primarily used in the entertainment simulation industry. Because of this, the manufacturer has already conducted extensive testing regarding the safety of this device. All potential safety hazards of the CMBS have been analyzed and when possible, tested, by TARDEC personnel. Because the CMBS has a very small motion envelope (±1.5 inches in the translation axes and ±15degrees in the rotational axes) and a low acceleration potential (0.4g's and 140 deg/sec^2 respectively), the risk of occupant injury due to motion is very small. The design features and safety devices for the CMBS, when used in conjunction with a TARDEC developed operating procedure, will reduce the probability of injury to occupants or damage to equipment.

4.0 RECOMMENDATIONS

Because of the small motion envelope and low acceleration capability of the CMBS, no additional safety interlock hardware/software is recommended. It is recommended, however, that signage be placed on or near the simulator describing the maximum payload (occupant) capacity and discouraging potential occupants who may have an existing medical condition (i.e. pregnant woman, persons with back problems or who are prone to motion sickness) from riding the simulator.

5.0 DISCUSSION

5.1 SYSTEM DESCRIPTION

The Cave Motion Base Simulator is a unique six (6) degree-of-freedom (DOF) motion platform. It is a COTS motion base manufactured by Tsunami Visual Technologies, Inc., Fremont, CA. This motion platform uses a combination of six electric rotary actuators, bell-cranks and push rods to connect a triangular fixed base with a triangular motion platform. Each of the six electrical rotary actuators are also connected to a potentiometer thru a belt-pulley system to determine the angle of the motor shaft. By controlling the shaft angle of each of the six electric rotary actuators, this mechanism provides for independent or simultaneous motion of the platform in the six natural DOF. An occupant seat is mounted to the upper platform.

The CMBS is composed of the following major subsystems:

- Motion Platform
- Electronic Controls
- Controller Software

Figures 5-1 and 5-2 are photographs of the CMBS and associated equipment.

Figure 5- 1 CAVE Motion Base Simulator (front view)

Figure 5- 2 CAVE Motion Base Simulator (Rear view)

5.2 SYSTEM PERFORMANCE

The maximum closed-loop performance of the CMBS motion platform is summarized below:

- Payload: 500 lb
- Performance capability per axis:

Axis	Displacement	Velocity	Acceleration
X (longitudinal)	± 1.5 in	± 10 in/s	± 0.4 g
Y (lateral)	± 1.5 in	± 10 in/s	± 0.4 g
Z (vertical)	± 1.5 in	± 10 in/s	± 0.4 g
Roll (about X)	± 15 °	± 30 °/s	± 140 °/s^2
Pitch (about Y)	± 15°	± 30 °/s	± 140 °/s^2
Yaw (about Z)	± 15°	± 30 °/s	± 140 °/s^2

Table 5- 1 Performance Summary

5.2.1 MAXIMUM SYSTEM ACCELERATION AND DECELERATION

A number of tests were performed on the CMBS to experimentally document the maximum acceleration of the motion base. A 3-axis accelerometer pad was fixed to the platform seat and then attached to an oscilloscope. The simulation software was configured to input a sine wave into each of the linear axes (independently). The amplitude and frequency of the sine wave was increased until a maximum acceleration was observed on the oscilloscope. In order to observe the maximum acceleration capabilities of the simulator, the occupant seat was left empty. This test was repeated in each of the linear axes. Figure 5-3 shows the transducer setup.

Figure 5- 3 Acceleration Test Transducer Setup

Due to the difficultly in setting up the controller software and running the actual test, it cannot be stated that these maximums are absolute. It can be stated that the data presented below is a best account of the maximum acceleration capacity of the CMBS for the conditions of this test.

Motion Direction	Input Amplitude	Input Frequency	Max Observed Acceleration
Along Z axis	1.7 cm	11 rad/s	0.4g
Along X axis	1.7 cm	11 rad/s	0.4g
About Y axis	1.7 cm	11 rad/s	0.4g

Table 5- 2 Measured Maximum Linear Accelerations

An example of the test data from which the above table was generated is shown in Figures 5-4 thru 5-6.

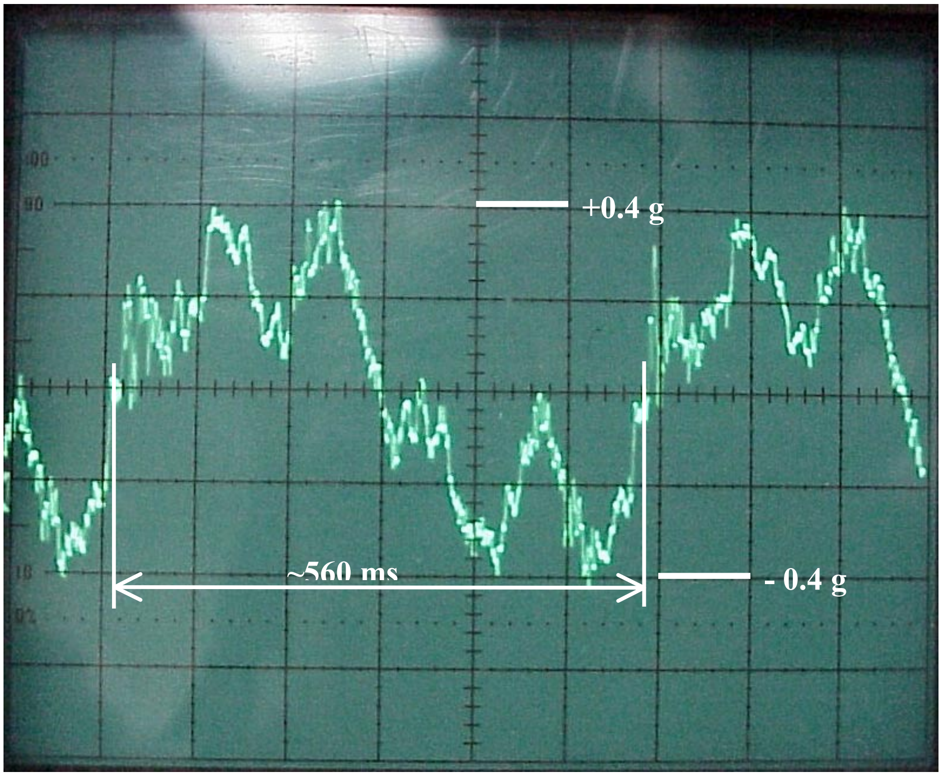

Figure 5- 4 X-Axis (Fore-Aft) Acceleration Trace

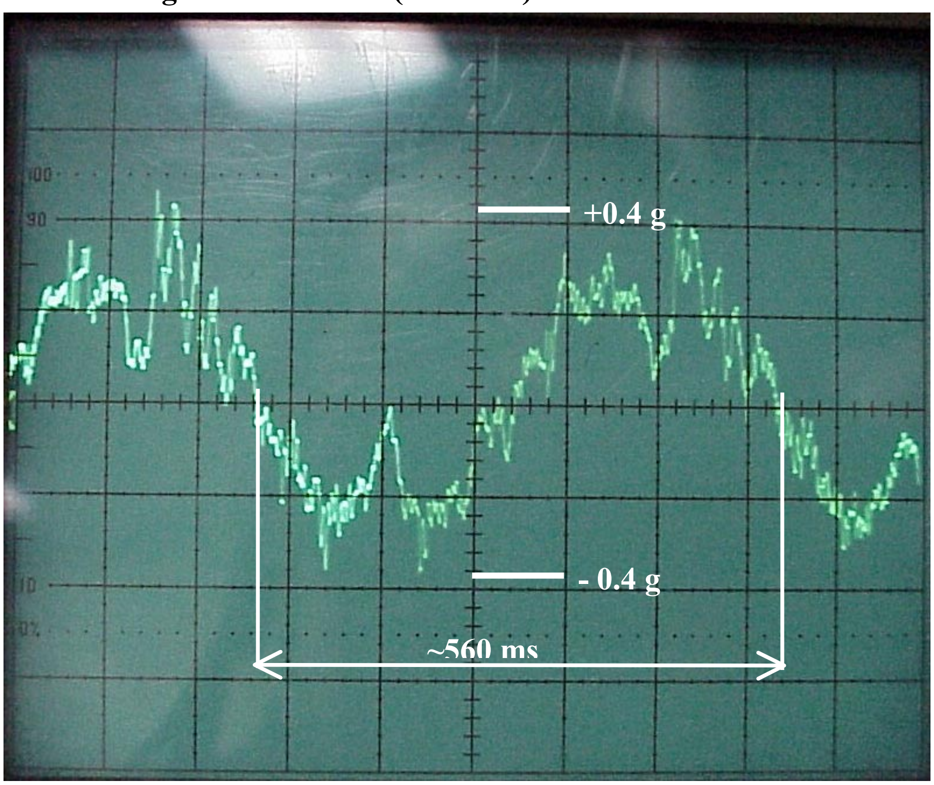

Figure 5- 5 Y-Axis (Lateral) Acceleration Trace

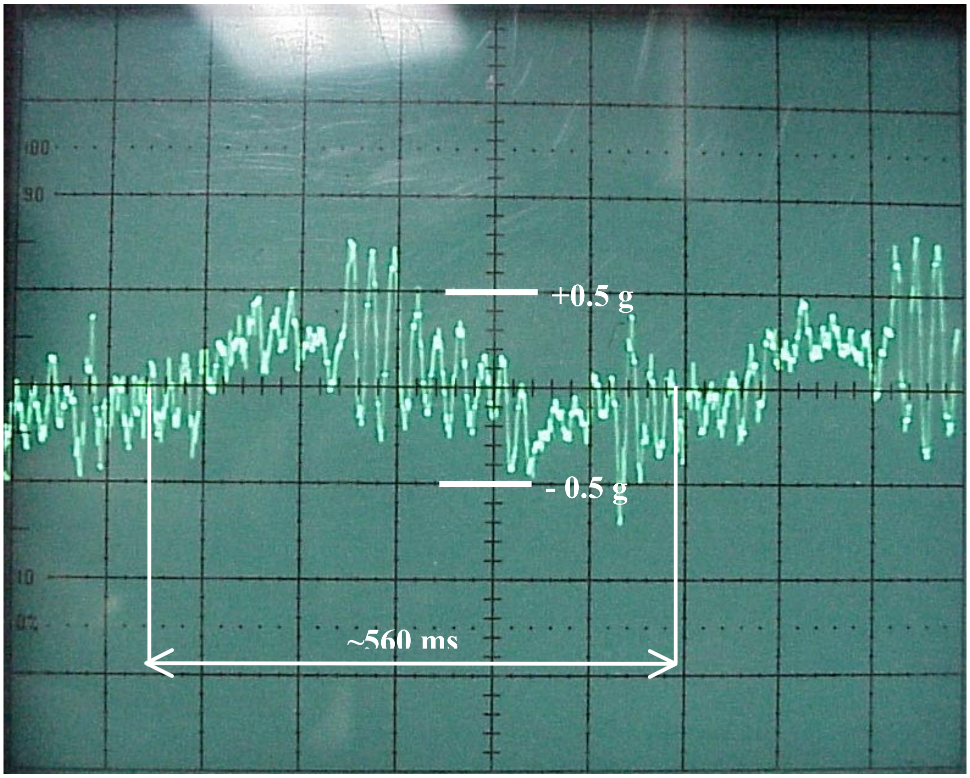

Figure 5- 6 Z-Axis (Vertical) Acceleration Trace

5.3 CMBS HAZARD EVALUATION

The analysis results presented on the following pages address the hazard potential to the Cave Motion Base Simulator should there be a failure in any of the CMBS subsystems.

The hazard assessment is divided into two parts as follows:

- A general safety analysis for each CMBS subsystem (Section 5.4)
- An analysis of each possible hazard, failure probability and backup system presented in table format (Section 5.5)

5.4 SAFETY ANALYSIS OF EACH SUBSYSTEM

This section provides a safety analysis of each of the following CMBS subsystems:

- Motion Platform (Subsection 5.4.1)
- Controller Software and PC (Subsection 5.4.2)

Each subsection provides a description of the subsystem, a structural integrity overview (if applicable), and an analysis of subsystem failures that may occur.

5.4.1 MOTION PLATFORM SAFETY ANALYSIS

The motion platform is composed of the following mechanical components:

- Platform Base
  - Actuators
  - Upper Platform

Each of these components is described in detail as follows.

Platform Base
The platform base consists of an aluminum box containing the electrical control box, all electrical wiring, the motor frame, and step up transformer. The platform base also includes leveling feet, retractable casters and provisions to bolt the base to the floor if necessary. The electrical control box, which resides inside of the platform base, contains the interfaces to the Personal Computer (PC) and consists of all the electrical components to control the rotary actuators. All of the electronic controls and electrical wiring were manufactured and installed to current industry standards. In addition, the electrical components were tested and certified by Underwriters Laboratory as conforming to the Standard for Amusement and Gaming Machines, UL22 and the Canadian Standard for Audio, Video and Similar Electronic Equipment, C22.2 No.1-98. UL judged the system eligible for Listing and Follow-Up Service and authorized the manufacturer to use the UL mark on the product (Note: The product tested by UL included the motion base, visual and audio systems sold together as an arcade. The CMBS and the motion base tested are identical in configuration and manufactured to the same standards).

Actuators
The actuator assembly consists of six electric rotary actuators along with the bell-crank/push rod assemblies. These are the active links, or legs, supporting the motion platform. The push rods are connected to the system at each end with a swivel. These items are all enclosed in a shroud to protect the occupant and any observers from the moving mechanical components.

Upper Platform
The upper platform consists of a triangular weldment, a seat attachment plate, and the occupant seat. The triangular weldment is the upper attachment point of the push rod assemblies. The seat attachment plate has tubular extensions to mount the simulation controls (i.e. steer and throttle controls), and an emergency stop button. It also has a t-bar extension for the occupant to place their feet. The occupant seat is mounted on the seat attachment plate and is made of a molded plastic. It has a high-back for occupant head/neck protection and large bolstering for lateral occupant stability.

5.4.2 CONTROLLER SOFTWARE AND PC SAFETY ANALYSIS

The PC that hosts the controller software is a 600MHz Pentium III PC running Microsoft Windows 98. The software, SimCreator, is a commercial product written by Realtime Technologies Inc. SimCreator is a graphical simulation and modeling system that is used for both the motion system and coordination of the graphical system in the CA VE. The motion control system handles all of the vehicle model dynamics and calculates the six required motor shaft positions in order to achieve the desired position of the motion base. It takes these six motor positions and outputs them to the motion base via a digital-to-analog convert card located in the host PC. The host PC also has a graphical user interface to start and stop a simulation. A failure to the host PC or controller software (i.e. controller software, operating system, D/A crash) does not induce any large displacements or accelerations into the motion base and is therefore not considered a risk to the safety of the occupant.

In addition, Table 5-3 lists CMBS failures and effects that were demonstrated to TARDEC's Safety Office before it could pass a safety release for man-rating.

Table 5- 3 CMBS Failure and Effects Table

Failure/Switch	Effect on RMS	Action Taken	Verified (initials)
Simulate power loss to interface (PC on console)	Simulator has slight jerk and moves to mid-position	Depress E-Stop. Reset power to PC and Resume.	
Simulate operator error on monitor (i.e. close window)	Simulator holds current position.	Depress E-Stop. Reset power to PC and Resume.	
Emergency stop button on operator console	Simulator stops and moves to rest position.	Reset simulation and resume.	
Emergency stop chain for Occupant	Simulator stops and moves to rest position	Reset E-Stop button to resume.	
Simulate power loss to simulator	Simulator stops and moves to rest position (gravity assist only)	Occupant to egress. Reset power and resume.	
PC/Simulator communications failure	Simulator holds current position.	Occupant depresses E-Stop and egresses. Fix communications and resume.	

5.5 SYSTEM HAZARD ANALYSIS

The accompanying analysis sheets contain hazard severity levels and hazard probability levels from MIL-STD-882C. These hazard levels allow system damage and personal injury to be included in the definition and reflected in the hazard assessment.

HAZARD SEVERITY LEVELS

a. Category I - Catastrophic. May cause death or system loss.

b. Category II - Critical. May cause severe injury, severe occupational illness, or major system damage.

c. Category III - Marginal. May cause minor injury, minor occupational illness, or minor system damage.

d. Category IV - Negligible. Will not result in injury, occupational illness, or system damage.

HAZARD PROBABILITY LEVELS

A - Likely to occur immediately

B - Probably will occur in time

C - Possible to occur in time

D - Unlikely to occur in time

Table 5- 4 SYSTEM HAZARD ANALYSIS TABLE

HAZARD	CAUSES	EFFECTS	HAZARD SEVERITY	HAZARD PROBABILITY	COMMENTS CORRECTIVE ACTION/MINIMIZING PROVISIONS
Impact/Crushing Physical Injury					
	Structural failure of servomotors, actuators, seat, and motion base frame	Possible damage to the CMBS depending on the locations and severity of structural damage	II	D	Since the mechanism design includes a bell crank hooked to a swivel and then a push rod, the worst case hazard is that one of these pieces of hardware completely breaks in half and the seat of the structure tips a little. If such an event would occur, the occupant or observer would press the E-stop button to trigger emergency shutdown. A conservative load limit of 500 pounds may mitigate this hazard. Following the maintenance schedule and a pre-test checklist will greatly reduce the possibility of this type of hazard as well.
	Structural failure of seat, other small components	Possible damage to the CMBS	II	D	Critical CMBS structure elements concerning human safety are the seat support. Failure of these elements could result in minor physical injury to the occupant. Although, this is unlikely given the distance of travel. If any of the seat components would fail, the seat would only tip slightly, leaving the occupant still seated. To mitigate this hazard, the CMBS was designed with a conservative limit load specification. Following the maintenance schedule and a pre-test checklist will greatly reduce the possibility of this type of hazard.
	Person entering area during test run	Possible physical injury to person	II	D	Access to around the CMBS area is limited to operation and maintenance personnel. All personnel should stay away from the simulator if while it is in operation.

HAZARD	CAUSES	EFFECTS	HAZARD SEVERITY	HAZARD PROBABILITY	COMMENTS CORRECTIVE ACTION/MINIMIZING PROVISIONS
Electrical shock					
	Wear or severing of power cables to CMBS	Electrical shock to personnel	II	D	Design is based on industry standards National Electrical Code. Voltage (110 VAC, 30 Amps, 50/60 Hz) is conduit enclosed per National Electrical code.

SYSTEM HAZARD ANALYSIS TABLE (con't)

HAZARD	CAUSES	EFFECTS	HAZARD SEVERITY	HAZARD PROBABILITY	COMMENTS CORRECTIVE ACTION/MINIMIZING PROVISIONS
Fire and Smoke Exposure	Ignition from spark or open flame	Possible severe damage depending on the extensiveness of the fire	II	D	It is highly unlikely that the actuators could burn since they are totally sealed mechanical units that are designed to be durable with low maintenance. Banning any open flames or smoking materials from the area will reduce the chance of fire to almost zero.

HAZARD	CAUSES	EFFECTS	HAZARD SEVERITY	HAZARD PROBABILITY	COMMENTS CORRECTIVE ACTION/MINIMIZING PROVISIONS
Sustained Physical Acceleration	Hardware or software failure or setup error which causes control instability	acceleration and deceleration is possible but is not high enough to cause any damage	II	D	Worst case scenario implies sinusoidal motion at the performance limits of the machine. The resulting largest acceleration/deceleration possible is 0.4 G's, too small to cause any physical or hardware damage. Pressure relief valves and hydraulic cushions prevent damage to machine. The CMBS operator can stop the test by pressing the master stop button, or the test subject can activate the E-stop button in the seat. Following the maintenance schedule and a pre-test checklist will reduce the possibility of this type of failure.

HAZARD	CAUSES	EFFECTS	HAZARD SEVERITY	HAZARD PROBABILITY	COMMENTS CORRECTIVE ACTION/MINIMIZING PROVISIONS
High Physical Acceleration	Loss of controller hardware, servomotor failure, shaft encoder, or cable failures	high acceleration possible before complete shutdown	III	C	Worst case scenario implies high acceleration. The resulting largest acceleration/deceleration possible is 0.4 G's, too small to cause any physical or hardware damage. The CMBS operator can stop the test by pressing the E-stop button, or the test subject can activate the E-stop button in the seat. Following the maintenance schedule and a pre-test checklist will reduce the possibility of this type of failure.

SYSTEM HAZARD ANALYSIS TABLE (con't)

HAZARD	CAUSES	EFFECTS	HAZARD SEVERITY	HAZARD PROBABILITY	COMMENTS CORRECTIVE ACTION/MINIMIZING PROVISIONS
High Physical Acceleration (con't)					
	Loss of integrity of external input signal to CMBS	Invalid signals sent to the CMBS from external device	III	D	All output data is filtered using the electronic filters which would smooth over any sudden changes in signal. Invalid signals should be detected in the testing phase before the test subject has boarded the simulator.
	Incorrect electrical connections	Undesirable movement of the simulator. Loss of control.	III	D	Changing the CMBS motion electrical connections is unlikely. Pre-simulation testing will reveal incorrect settings of the control modules or incorrect hookups of the input signal. Corrections will then be made. Also, a preliminary dry run each morning will greatly reduce the possibility of this type of hazard.

HAZARD	CAUSES	EFFECTS	HAZARD SEVERITY	HAZARD PROBABILITY	COMMENTS CORRECTIVE ACTION/MINIMIZING PROVISIONS
Minimal.					
	Loss of input line voltage to CMB control electronics	Loss of electrical power to CMB control electronics	N.A.	C	If the input line voltage is lost the simulator will halt immediately. The occupant is to press the E-stop. The E-stop will be detected thus triggering emergency shutdown, the simulator will level itself.

ACRONYMS

CMBS	CAVE Motion Base Simulator
DOF	Degree of Freedom
HUC	Human Use Committee
Hz	Hertz
MBT	Motion Base Technologies
NAC	National Automotive Center
PSL	Physical Simulation Laboratory
RDTE	Research, Development, Test and Evaluation
TACOM	Tank-automotive and Armaments Command
TARDEC	Tank Automotive Research, Development and Engineering Center